

ADVANCED HIGH AND LOW FIDELITY HPC SIMULATIONS OF FCS CONCEPT DESIGNS FOR DYNAMIC SYSTEMS

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ABSTRACT

The Objective Force concept of the future US Army is to fight wars with adversaries, which are fast evolving and have adaptive capabilities. To have advantage over these adversaries, new weapon system designs and development should be modular to operate as “system-of-systems” and should have short development cycles. This requires validated high performance computational models within this modular framework and the need to effectively utilize the High Performance Computing (HPC) resources of many Army initiatives. In this paper we present a new and advanced HPC based rigid and flexible modeling and simulation technology capable of adaptive high/low fidelity modeling that is useful in the initial design concept stage to intermediate stages and to the final design stage in a single seamless simulation environment. Two examples are considered that illustrate the capabilities and scalability of the proposed approach.

1. INTRODUCTION

Traditionally, dynamic analyses of a vehicle system employing HPC are performed considering the components of the vehicle systems as rigid (Letherwood and Gunter, 2001) for providing an understanding and controlling of the gross motion of the system such as the roll angle, pitch angle, steering angle for ride quality, etc. The assumption that the bodies are rigid is reasonable as the traditional vehicle/weapon systems are big and heavy. To have an advantage over the adversaries, weapon systems that are strategically responsive, deployable, agile, and lightweight combat systems are required. To consider the components to be rigid in these situations could render the prediction of weapon system performance erroneous. The rigid and flexible modeling environment has traditionally been one in which independently developed and validated codes were used to analyze different sub-systems. This is accomplished by coupling two different codes, namely, rigid-body dynamic analysis capabilities with finite element analysis software.

It is increasingly being recognized that there is no shortage of multi-disciplinary software codes available especially on serial computing environments to perform

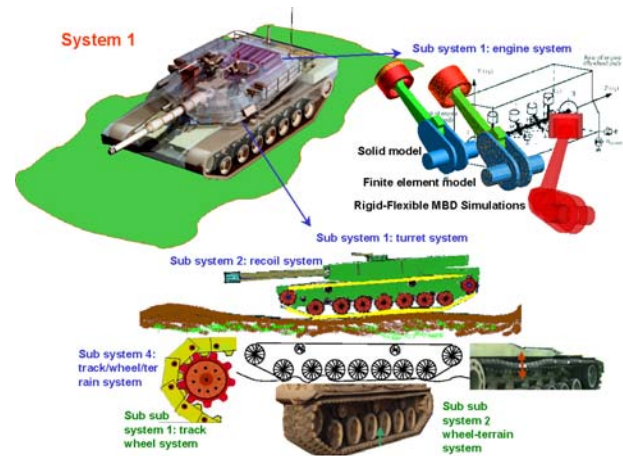


Figure 1. Typical weapon system consisting of several sub-systems. This illustrates that an entire vehicle-track system is a complex system with many sub-systems and within each sub-system different parts require varying degree of fidelity modeling capability in rigid and flexible multi-body simulation code.

various simulations. However, what is desired is fewer codes that can solve more problems for the design engineer in a HPC computing environment. More importantly, a unified coupled approach is required to avoid any errors in interfacing multi-physics code, as there is no unique way of coupling it (Pan and Haug, 2001). These errors in the uncoupled approach are highlighted in the literature and few of them are cited here. For example: 1) the deformation of the single bodies cannot be computed accurately by means of an uncoupled rigid body multiple body system and using the computed inertial forces of the multiple body system (Gerstmayr, 2001), 2) accurate stress computations requires special treatment. For example, proper design of the so-called quasi-comparison functions (combination of eigenfunctions and static deformation modes to represent body deformation in the small deformation regime) has shown to improve stress representation in the flexible bodies (Schwertassek et al., 2001), 3) standard approaches in commercial software for 3D multiple body systems that use component mode synthesis in order to reduce the number of degrees of freedom shows a lack in the modeling of contact and material non-linearities, 4) it is

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not readily suitable for bodies undergoing large deformations (Ibrahimbegovic et al., 2000). These are highly critical in the Objective Force concept because the design of a complex weapon system can consist of many sub-system designs, and an integrated modeling and testing environment may suffer from these inaccuracies. A typical illustration of a complex system is described in Fig. 1.

Computer simulation of multiple body dynamical systems requires accurate, efficient and robust time integration schemes to handle complexities of high index differential-algebraic equations (DAE). Towards this end we use the primal-dual methodology developed by Kanapady et al., 2003 and Kanapady et al. 2004, which overcomes many computational challenging issues, namely, constraint preservation, preserving order of accuracy of time integration operators and faster convergence rates of nonlinear iterations for the solution of multi-body dynamical DAE.

At the AHPCRC/University of Minnesota, we have developed an advanced HPC computational technology that simultaneously accounts for different levels of modeling resolution of both rigid and flexible multiple body systems dynamics simulation in a single analysis code in a seamless manner. The different resolution levels include: i) lowest level resolution where all the bodies are considered rigid, (ii) mid-level resolution where each body can be rigid or elastic, including interactions between bodies, and (iii) highest level of resolution where each body can be rigid, elastic, or the bodies can undergo nonlinear geometric and material deformations. These new developments are based solely on converting the state-of-the-art finite element analysis code rather than

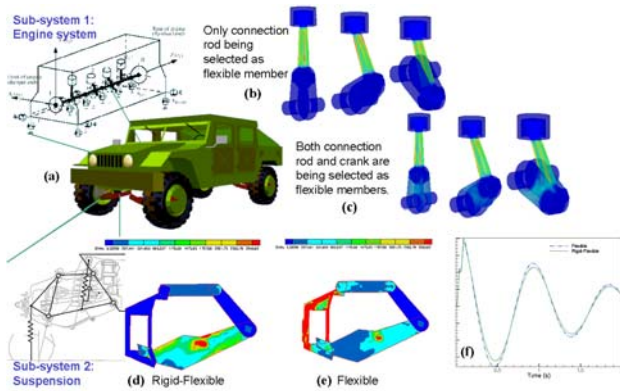


Figure 2. (a) Illustration of rigid-flexible multiple body analysis of engine and suspension sub-system, (b) and (c) crank-connecting rod-piston mechanism 3D configurations at different times for two different selections of degree of flexibility, (d) and (e) suspension system with varying degree of flexibility, (f) displacement time history at midpoint of lower arm for configuration (d) and (e).

converting a state-of-the-art rigid body analysis code. A unified code therein minimizes human errors and approximation errors in coupling different physics based codes such as a rigid body dynamics code to a finite element analysis code. On the outset, the small-scale simulation results employing the developed code for a hummer vehicle system is illustrated in Fig. 2. In these simulations the present software automatically reduces the selected finite elements to rigid-bodies that are specified according to the designers' simulation needs.

While the Objective Force places new challenges, achieving short design cycles simultaneously demands advanced simulation capabilities in the software, as new operating scenarios need to be considered. For example, in the case of multitask armored vehicle, in addition to traditional stand of firing, precision firing on the move capability is needed. The firing stability analysis of the entire vehicle, recoil mechanism analysis, rounds auto loader system analysis at higher rates needs to be analyzed along with the ride quality prediction in the above operating conditions. The accurate modeling of these scenarios at each stage of the design stage not only requires varying degree of fidelity modeling but also requires that the formulations used in their description account for large motion and deformation of their components. In addition, it should also describe their correct structural interactions via inertial coupling between various rigid and flexible bodies.

Depending on the selected number of components of the entire vehicle as flexible components the number of equations that needs to be solved are in the order of millions. Hence, the primary objective of this research is to develop and demonstrate a scalable HPC simulation environment to accurately model new weapon system designs at varying level of fidelity. The present research efforts are focused on delivering this end product for Army initiatives and to successfully demonstrate the effectiveness to the Objective Force. The scalable software significantly reduces the run times for a favorable design cycle and simplifies the acquisition process for the U.S. Objective force goals.

2. FLEXIBLE COMPONENT MODELING

The differential equations governing the motion of a flexible body Ω are given by

$$\begin{aligned} \rho \ddot{\mathbf{u}} - \nabla \cdot \boldsymbol{\sigma} - \mathbf{b} &= 0 \text{ in } \Omega \\ \boldsymbol{\sigma} \cdot \mathbf{n} &= \mathbf{t} \text{ on } \Gamma_{\sigma} \\ \mathbf{u} &= \mathbf{u}^* \text{ on } \Gamma_u \end{aligned} \quad (1)$$

where, the boundary Γ of the body is decomposed into two parts Γ_{σ} and Γ_u , \mathbf{u} are the displacements, ρ is the mass density of the body Ω , $\boldsymbol{\sigma}$ is the true stress, ∇ represents the

divergence operator with current coordinates, \mathbf{b} is the body force, \mathbf{t} are the prescribed tractions and \mathbf{u}^* are the prescribed displacements.

Although considering a body as rigid can lead to significant computational savings, it models the motion of a body accurately only in the case when the deformations are small. Thus, in view of the current objectives of simulating agile and lightweight combat systems, which may undergo large deformation, a model consisting solely of rigid bodies would not be accurate. One therefore resorts to modeling the flexible body by discretizing the equation of motion in space using numerical or modal techniques.

Considerable research has been done during the past decades for modeling equations of motion of deformable bodies. Based on the choice of reference frame chosen to represent the deformation of points on flexible bodies, these approaches can be classified as: 1) floating frame approach (Meirovitch and Nelson, 1967), in which an intermediate frame, which decouples the rigid and flexible motion, is defined for each flexible component and the deformations are referred to this frame. Although a natural way to extending the rigid body, this approach is limited to modeling flexible bodies undergoing small deformations, 2) co-rotational approach (Belytschko and Hsieh, 1973), in which an intermediate frame, which decouples the rigid and flexible motion, is defined for each finite element. Although this approach can be applied for large deformation problems it is more appealing in the case of small deformations for which linear elasticity can be used, and 3) inertial approach (Bathe et al., 1975), in which no intermediate frame is used and all the displacements are referred to the inertial frame. In the current software the inertial approach is used due to its ability to accurately model large deformation and rotations. The equations of motion of a flexible body after carrying out space discretization using the finite elements, in conjunction with the inertial approach, can be written as:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{p}(\dot{\mathbf{u}}, \mathbf{u}) = \mathbf{f}$$

$$\mathbf{M} = \bigcup_{e=1}^{n_e} \mathbf{L}^{(e)T} \int_{\Omega_e} \mathbf{N}^T \mathbf{N} d\Omega \quad (2)$$

$$\mathbf{p} = \bigcup_{e=1}^{n_e} \mathbf{L}^{(e)T} \int_{\Omega_e} \mathbf{B}^T(\mathbf{u}) \mathbf{S} d\Omega$$

$$\mathbf{f} = \bigcup_{e=1}^{n_e} \mathbf{L}^{(e)T} \left[\int_{\Omega_e} \mathbf{N}^T \mathbf{b} d\Omega + \int_{\Gamma_e \cap \Gamma_\sigma} \mathbf{N}^T \mathbf{t} dA \right]$$

where, \mathbf{M} is the mass matrix, \mathbf{p} is the vector of the non-linear internal forces including elastic and damping contributions, \mathbf{f} is the vector of externally applied forces, $\mathbf{L}^{(e)}$ is the element connectivity matrix, \mathbf{S} is the vector form of the second Piola-Kirchhoff stress, \mathbf{N} is the shape function matrix, \mathbf{B} is the compatibility matrix which

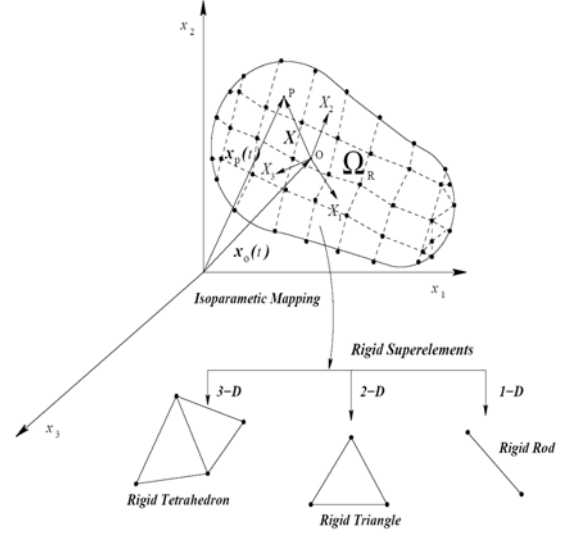


Figure 3. Rigid body Ω_R mapped into a rigid superelement, consistently reducing the finite element model and providing the framework for high/low fidelity modeling.

relates the virtual strains to the virtual nodal displacements for non-linear elasticity and relates strains to nodal displacement for linear elasticity.

3. RIGID COMPONENT MODELING

For accurate modeling, ideally, one would like to consider all the components in complex weapon system as flexible. Although accurate, this approach is not ideally suited for initial and intermediate design stages due to the high computational cost associated with detailed modeling of complex systems. To reduce the computational cost one of the popular approaches involves the modal reduction, wherein static deformation modes are used to represent the small deformations of a component. For a more general case of large deformation, the modal reduction cannot be used due to the internal forces being a non-linear function of displacements. Another approach to the cost reduction involves the modeling of components using the rigid body hypothesis, which can easily be used in the case when other flexible components undergo large deformation. For designing new weapon system in the shortest possible time, one can therefore use the capability of adaptive high/low fidelity modeling, whereby the design can first be evaluated by assuming most of its components to be rigid. Subsequently, after knowing the contribution of each component to the flexibility of the model the number of rigid components can be reduced in a consistent manner towards final design stages. Thus, achieving the objective of accurate modeling of new weapons system together with a short development cycle. In order to provide the designer with the capability to collapse the selected finite elements to a rigid body that reduces the computational

cost of the model significantly, we have used the approach presented by Taylor, 2001. This approach, shown in Fig. 3, involves mapping the finite element mesh associated with the component, considered rigid, into a single rigid body super-element using the standard isoparametric mapping. This super-element could be a rod, triangle or a tetrahedron depending on the case of modeling edge, surface or volumetric rigidity. Thus, the equation of motion of a rigid body by collapsing its associated finite elements can be written as

$$\mathbf{M}_r \ddot{\mathbf{u}}_r + \mathbf{G}(\mathbf{u}_r) \boldsymbol{\mu}_r = \mathbf{F}_r \quad (3a)$$

$$\boldsymbol{\varphi}_r = 0 \quad (3b)$$

$$\mathbf{M}_r = \sum_{i=1}^{n_e} \mathbf{N}_i^T \mathbf{M}_i^{(e)} \mathbf{N}_i \quad (4)$$

where, \mathbf{u}_r are the displacements of the rigid super-element, $\boldsymbol{\varphi}_r$ are the constraint equations restricting the edge length of the rigid super-element to remain constant, $\mathbf{G}(\mathbf{u}_r)$ is the constraint jacobian, $\boldsymbol{\mu}_r$ are the Lagrange multiplier imposing the constraints, \mathbf{M}_r is the equivalent mass matrix of the rigid super-element, \mathbf{F}_r is the equivalent force vector, \mathbf{N}_i is the shape function matrix of the i^{th} element, $\mathbf{M}_i^{(e)}$ is the mass matrix of the i^{th} element.

4. CONSTRAINTS IN RIGID-FLEXIBLE SYSTEMS

In a multiple body system such as a vehicle, etc., the interactions between flexible and/or rigid bodies are defined by constraints. A joint or kinematic pair imposes constraints on the relative motion of the two bodies defining the pair. These constraints enable the motion of a multiple body system to be useful for a particular task by reducing the number of degrees of freedom of the system.

4.1 Holonomic Constraints

Holonomic constraints arise if the constraint equations are an implicit function of the nodal displacements and time. One simple example of holonomic constraint is a revolute or hinge joint used in the vehicle systems to robotic manipulator. A revolute joint is formed when two bodies are pinned together, thus restricting the relative motion between the two bodies to one rotation about a specific axis.

$$\boldsymbol{\varphi}(\mathbf{u}, t) = 0 \quad (5)$$

4.2 Non-Holonomic Constraints

Constraints, which are functions of velocities or inequality constraints that cannot be integrated back to the

form of holonomic constraints, are called non-holonomic constraints. In vehicle dynamics the constraint for pure rolling of the wheel is a case of non-holonomic constraint.

$$\boldsymbol{\varphi}(\mathbf{u}, \dot{\mathbf{u}}, t) = 0 \quad (6)$$

4.3 Equation of motion for Constrained Systems

The equation of motion of system, which satisfies the constraints imposed on it, can be written by imposing the constraints using the Lagrange multipliers

$$\mathbf{M} \ddot{\mathbf{u}} + \mathbf{C} \dot{\mathbf{u}} + \mathbf{p}(\mathbf{u}) + \mathbf{G}^T(\mathbf{u}, t) \boldsymbol{\mu} = \mathbf{F} \quad (7a)$$

$$\boldsymbol{\varphi}(\mathbf{u}, t) = 0 \quad (7b)$$

the above equations of motion Eq. (7a-b) is a differential equation for \mathbf{u} , which depends on the Lagrange multiplier or algebraic variable $\boldsymbol{\mu}$, and the solution is forced to satisfy the algebraic constraints $\boldsymbol{\varphi}$, where \mathbf{G} is the jacobian of constraints. Thus the equations of motion of a constraint system are called differential algebraic equations (DAEs).

5. ROBUST SIMULATION TECHNIQUE FOR CONSTRAINED SYSTEMS

Computer modeling and simulation of multibody dynamical systems requires accurate, efficient and robust implicit time integration schemes to handle complexities of high index DAEs. The difficulties associated with the application of ordinary differential equation (ODE) methods to the solution of such DAEs are: (i) they are prone to numerical instability for symplectic integrators (ii) induce constraint violation leading to unphysical solutions, and (iii) leads to order reductions for stiff integrators. It is particularly difficult to obtain an accurate solution for the algebraic variable, Lagrange multipliers. In addition, often, the velocity, accelerations and Lagrange multipliers suffer from an order reduction. To overcome several of these difficulties we use the primal-dual technique.

The weak form of semi-discretized equation of motion of a multiple body system subjected to constraints using any standard time integrator can be represented as

$$\mathbf{M} \ddot{\hat{\mathbf{u}}}_{n+1} + \mathbf{C} \dot{\hat{\mathbf{u}}}_{n+1} + \mathbf{p}(\hat{\mathbf{u}}_{n+1}) + \mathbf{G}^T(\hat{\mathbf{u}}_{n+1}) \hat{\boldsymbol{\mu}}_{n+1} = \hat{\mathbf{F}}_{n+1} \quad (8a)$$

$$\boldsymbol{\varphi}(\mathbf{u}_{n+1}, t) = 0 \quad (8b)$$

$$\boldsymbol{\varphi}(\mathbf{u}_{n+\frac{1}{2}}, \dot{\mathbf{u}}_{n+\frac{1}{2}}, t) = 0 \quad (8c)$$

where, $\hat{\mathbf{u}}_{n+1}$, $\dot{\hat{\mathbf{u}}}_{n+1}$, $\ddot{\hat{\mathbf{u}}}_{n+1}$ and $\hat{\boldsymbol{\mu}}_{n+1}$ are differential and algebraic state variables at time $\hat{t}_{n+1} \in [t_n, t_{n+1}]$. Constraints, which do work on the system, can lead to unstable time integration of the equation of motion. Therefore, the

holonomic constraint equations Eq. (8a) are satisfied using displacements computed at the end of the time step and non-holonomic constraint equations Eq. (8b) are satisfied using displacements and velocities computed at the mid-point which result in workless constraints. Linearizing the equation of motion Eq. (8a) with respect to the position \mathbf{u} and setting the resulting residual equal to zero, we get

$$\bar{\mathbf{M}}_{\mathbf{u}} \Delta \mathbf{u}_{n+1}^{j+1} = \bar{\mathbf{R}}_{\mathbf{u}} - \hat{\mathbf{G}}_{n+1}^j \mathbf{T} \hat{\boldsymbol{\mu}}_{n+1}^j \quad (9)$$

where,

$$\begin{aligned} \bar{\mathbf{M}}_{\mathbf{u}} &= [\ddot{\mathbf{u}}_{\mathbf{u}} \mathbf{M} + \dot{\mathbf{u}}_{\mathbf{u}} \mathbf{C} + \mathbf{u}_{\mathbf{u}} \mathbf{K}_t] \\ \bar{\mathbf{R}}_{\mathbf{u}} &= \hat{\mathbf{F}}_{n+1} - \mathbf{M} \ddot{\mathbf{u}}_{n+1} - \mathbf{C} \dot{\mathbf{u}}_{n+1} - \mathbf{p}(\hat{\mathbf{u}}_{n+1}) - \mathbf{G}^T(\hat{\mathbf{u}}_{n+1}) \hat{\boldsymbol{\mu}}_{n+1} \end{aligned}$$

linearizing the algebraic equation Eq. (8b) with respect to the position \mathbf{u} , we get

$$\boldsymbol{\phi}_{n+1}^{j+1} \approx \boldsymbol{\phi}_{n+1}^j + \mathbf{G}_{n+1}^j \Delta \mathbf{u}_{n+1}^{j+1} \quad (10)$$

in order to satisfy the constraint equation, the value of $\Delta \mathbf{u}$ is substituted from Eq. (9) into the linearized constraint equation Eq. (10) and setting the resulting residual equal to zero, yielding

$$\mathbf{G}_{n+1}^j \bar{\mathbf{M}}_{\mathbf{u}}^{-1} \hat{\mathbf{G}}_{n+1}^j \mathbf{T} \hat{\boldsymbol{\mu}}_{n+1}^j = \boldsymbol{\phi}_{n+1}^j + \mathbf{G}_{n+1}^j \bar{\mathbf{M}}_{\mathbf{u}}^{-1} \bar{\mathbf{R}}_{\mathbf{u}} \quad (11)$$

from the above equation the dual variable, $\boldsymbol{\mu}$ can be solved first and subsequently the primary variables such as \mathbf{u} , $\dot{\mathbf{u}}$, $\ddot{\mathbf{u}}$ can be recovered from Eq. (9) in an iterative procedure. This results in the preservation of constraints and all the underlying properties of the ODE time integrators and the accurate solution of Lagrange multipliers. Thereby, it provides an accurate, efficient and robust time integration scheme for index 3 DAE systems encountered in flexible multiple body systems.

6. SCALABLE HPC DEVELOPMENTS

The idea of a single multiple body dynamics simulation code which can handle different levels of modeling resolution, from predominantly rigid to predominantly flexible, is critical for the Objective force concept in which accuracy of results together with short development cycle are of utmost importance. To the best of our knowledge there is no single scalable code available which can meet the above objectives.

To develop a scalable HPC simulation environment, which is platform independent and can be ported to different HPC architectures, we use message-passing interface (MPI). The parallelization of simulation code involves parallel mesh and joint partitioning, implicit scalable solver technology and parallel visualization.

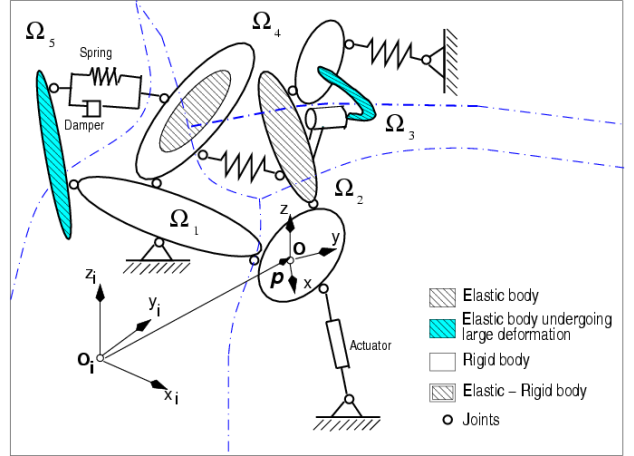


Figure 4. Illustration of partitioning of a rigid-flexible multiple body system for parallel processing.

6.1 Mesh Partitioning

The first stage of parallization involves partitioning of the finite element mesh into sub-domains as shown in Fig. 4. Each sub-domain is then attributed to a processor with the objective of balancing the computational loads and minimizing the communications between all the processors such that one can, ideally, achieve perfect scalability (linear reduction/speed-up in execution time when the problem size is kept constant).

In the present approach, the rigid body super-element is formed by collapsing many finite elements, thereby reducing the contribution of these elements to the total computational load. If the finite element mesh is now, naively partitioned by giving equal weight to each finite element the computational loads would be highly unbalanced between processors. We thus apply a multi-constraint mesh partitioning on the finite element mesh where the group of finite element that finally are mapped to a rigid super-elements are given less weight than the flexible elements which can deform.

6.2 Parallel Solution of the Equations of Motion

Joints between rigid bodies are distributed among processors such that each joint is attributed to a unique processor. The constraints and the Jacobian of constraints are thus partitioned as

$$\mathbf{B} = \begin{bmatrix} \cdot & \cdot & \mathbf{P}_1 & \cdot & \cdot \\ \cdot & \cdot & \mathbf{P}_2 & \cdot & \cdot \\ \cdot & \cdot & \dots & \cdot & \cdot \\ \cdot & \cdot & \mathbf{P}_{n-1} & \cdot & \cdot \\ \cdot & \cdot & \mathbf{P}_n & \cdot & \cdot \end{bmatrix} ; \quad \boldsymbol{\phi} = \begin{bmatrix} \mathbf{P}_1 \\ \mathbf{P}_2 \\ \dots \\ \mathbf{P}_{n-1} \\ \mathbf{P}_n \end{bmatrix} \quad (12)$$

The above partitioning scheme for joints naturally leads to row partitioning of constraint residual vector and constraint jacobian matrix. This easily lends to the parallelization of the dual solve given by Eq. (11) without modifying existing parallel finite element technology which is highly scalable.

The primal and dual solve which involve the solution of \mathbf{u}_{n+1} , $\dot{\mathbf{u}}_{n+1}$, $\ddot{\mathbf{u}}_{n+1}$ and $\boldsymbol{\mu}_{n+1}$ for serial computing is given by Eq. (9) and Eq. (11), respectively, for any popular implicit time integration scheme. The parallel implementation for the solution of these variables involves the use of highly scalable FETI-DP solver. We, first solve for vector $\hat{\mathbf{S}}_{n+1}$ given by Eq. (13), which is the incremental solution vector for non-linear dynamic problem without constraints

$$\overline{\mathbf{M}}_u \hat{\mathbf{S}}_{n+1} = \overline{\mathbf{R}}_u \quad (13)$$

to compute solution vector which satisfies the constraints, matrix $\hat{\mathbf{H}}_{n+1}$ is first solved for by using Eq. (14)

$$\hat{\mathbf{H}}_{n+1} = \overline{\mathbf{M}}_u^{-1} \hat{\mathbf{G}}_{n+1}^j \mathbf{T} \quad (14)$$

The Solution of dual variable, $\boldsymbol{\mu}$, now involves only a local solve

$$\mathbf{G}_{n+1}^j \hat{\mathbf{H}}_{n+1} \hat{\boldsymbol{\mu}}_{n+1}^j = \boldsymbol{\varphi}_{n+1}^j + \mathbf{G}_{n+1}^j \hat{\mathbf{S}}_{n+1} \quad (15)$$

and the primary solution vector can be recovered using a local update

$$\Delta \mathbf{u}_{n+1}^{j+1} = \hat{\mathbf{S}}_{n+1} - \hat{\mathbf{H}}_{n+1} \hat{\boldsymbol{\mu}}_{n+1}^j \quad (16)$$

7. RESULTS

In this section the following capabilities of the present software, namely, 1) high/low fidelity modeling, large rotation and deformation, and 3) scalability are

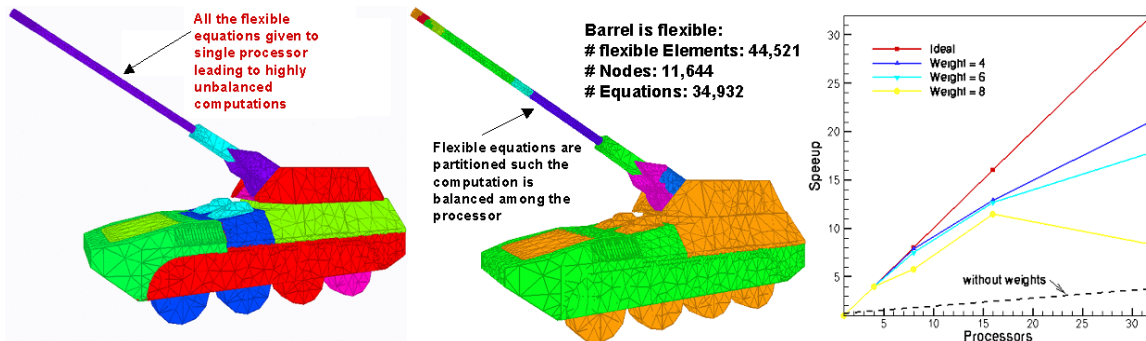


Figure 6. (a) Uniformly weighted mesh partitioning, (b) rigid-flexible weighted mesh partitioning, and (c) parallel performance comparison for different graph node weighting and without weighting.

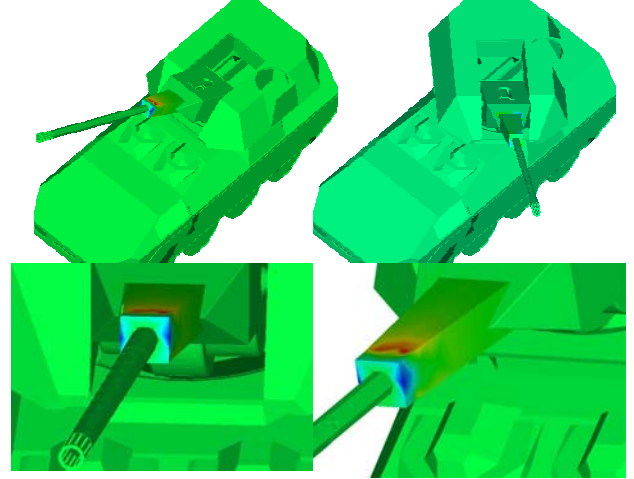


Figure 5. Illustration of increased fidelity analysis of gun barrel support (accurate stress prediction) in conjunction with bearing force prediction at turret and chassis interaction during turret rotation.

demonstrated by using the Original MRAAS FCS Concept Design provided by UDLP.

7.1 Turret Rotation Maneuver

In this numerical test, a torque is applied on the turret of the MRAAS, which serves the purpose of rotating the turret so that the MRASS can target the enemy. We first illustrate the adaptive capability of the code to select flexible and rigid components, which together with reducing the computational effort can predict stresses and deformation in the critical components accurately. Figure 5 shows the two different simulation frames of MRAAS modeled with barrel support as flexible, rest of the components of the vehicle are considered to be rigid. The simulation is able to accurately predict the stresses on the barrel support, which the designer might view to be a critical component during this maneuver. We also use this simulation, to illustrate the importance of non-uniform mesh partitioning when only the barrel is considered to be flexible and the rest of the vehicle is assumed to be rigid. Figure 6a and 6b shows the mesh partitioning obtained by

using uniform weights and the present scheme of attaching high weights to flexible elements. Figure 6c, shows the parallel performance while using different weighing schemes. It is apparent from Fig. 6c that giving uniform weights to elements results in a highly unbalanced computational loads between processors, thereby deteriorating the parallel performance severely. The results are much better for the cases when flexible elements are highly weighted.

7.2 Firing Analysis

The firing analysis of the MRAAS is a critical simulation, which can predict the dynamic behavior (both the gross motion together with deformation) of the vehicle during the case of stand of firing and firing on the move. Here applying the firing load on the recoil housing simulates the former case. The load time history is shown in the shown in Fig. 7. To study the parallel performance of the simulation code we employ a large finite element model containing one million flexible elements in the barrel and recoil-housing component. The parallel speed-ups are shown in the Fig. 8. It is evident from Fig. 8 that the code is highly scalable and achieves close to linear speedups up to 128 numbers of processor for this large-scale problem. This flexible dynamic analysis scalability results are highly noteworthy in comparison to the scalability results of direct and iterative solvers employed in commercial software ABAQUS, 2004 for similar problem size.

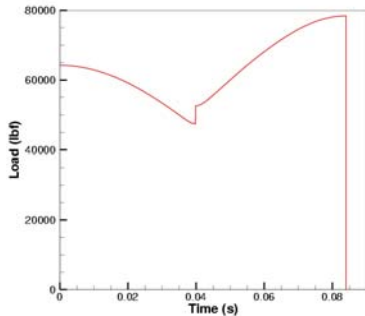


Figure 7. Load-time history for firing analysis.

To demonstrate the large deformation capability of the code, the barrel stiffness was reduced. In this simulation the barrel together with barrel support are consider flexible, the rest of the model is assumed to be rigid. Fig. 9 shows the simulation frame of the firing analysis. It is evident from Fig. 9a – 9c that the barrel undergoes large deformation due to its low stiffness and high loads associated with firing. The current software also helps the designer by predicting the stresses in these flexible components. Fig. 9d – 9f, which shows the acceleration contours, can be used to predict the gravity (“G”) force in the crew capsule and other sensitive areas.

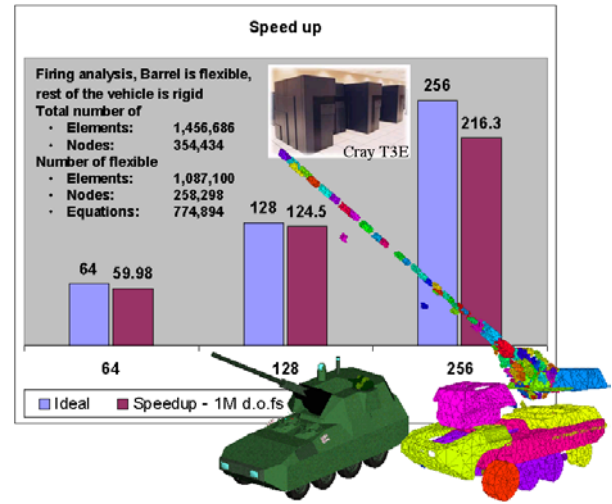


Figure 8: Highly scalable parallel performance of implicit primal-dual flexible-rigid body dynamics computations of the flexible gun barrel firing analysis of original of MRAAS FCS design concept UDLP.

CONCLUSIONS

The present work focuses on developing a single scalable HPC simulation environment to accurately simulate the new weapon system designs at varying level of fidelity, in view of the Objective Force concept of the future US Army described earlier.

The varying level of fidelity modeling which helps achieve the objective of accurate modeling of new weapons system together with a short development cycle is implemented by using non-linear finite element approach to model flexible components undergoing large deformation and the rigid body hypothesis for other components.

The robust simulation of equations of motion of these new complex weapon systems by a scalable HPC technology was accomplished by incorporating primal-dual technique for solution of index-3 DAEs and highly scalable FETI-DP solver.

The capabilities of the software developed were demonstrated by simulating the original MRAAS FCS concept design. It is evident by these simulation, which involve the rotation of the MRAAS turret and stand on firing, that the present HPC code is highly scalable and also provides the designer the capability of modeling the weapon system with components which can be assumed to be either rigid or flexible.

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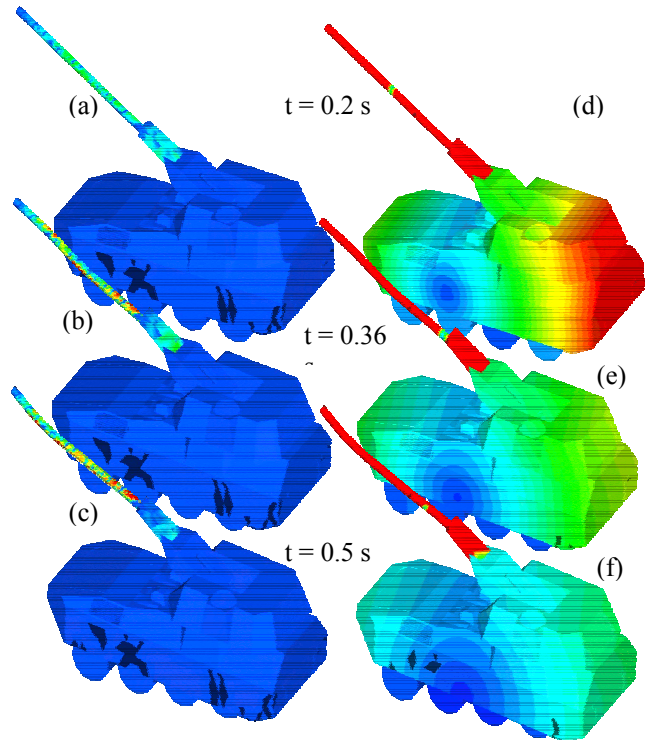


Figure 9. (a) – (c) Von-Mises stress contour plot, (d) – (f) acceleration contour plots during firing analysis of MRAAS with flexible gun and barrel support, at different time instants.